THERMOFORMING - ITS PROCESSES AND APPLICATIONS

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I. Introduction

Developments in the forming of thermoplastic sheet material might be likened to the growth and development of Africa. Until recently, few people were aware of its importance and potential. So too with thermoforming, which was one of the earliest methods of fabricating thermoplastic materials. With the advent of injection molding, most people felt thermoforming offered little, if any, future or growth potential. Thermoforming was generally regarded as a relatively inexpensive way of making a small number of plastic parts. Normally, if the application grew and warranted large volume production, it was taken over by injection molding. The last few years have altered this trend of thought considerably. This change has been brought about largely through the introduction of new forming materials, which in turn has encouraged the development of new forming machines and forming techniques and has brought this industry to a position of new strength in the thermoplastic fabrication field.

The applications in which thermoforming of plastic sheet is used are many and varied. Some of the applications are as follows:

Refrigeration

Inner door liners
Food compartments
Crisper trays

Packaging

Contour skin packages
Blister packages
Container lids
End caps for composite cans
Cottage cheese containers
Hot drink cups

Automotive

Air ducts
Crash pads
Arm rests

Signs and displays

Military

Contour maps
Airplane canopies

Industrial

Machine housings
Tote Boxes
Furniture components

The thermoforming process has many unique features when compared to the more familiar process of injection molding. These features have allowed the process to develop rapidly for certain applications, but have restricted its growth in others. The most outstanding advantages include:

1. Low mold and equipment cost allow formed parts to be produced in small quantities at relatively low cost.

2. Lower mold cost for full production molds have allowed stylists greater freedom in changing designs, even multiple molds are relatively inexpensive.

3. Ease of forming large area parts has made practical the production of shapes such as signs, panels and refrigerator door liners.

4. The ability to form thin walled (.015" and under) sections on multiple molds at high production rates has made thin walled lightweight packages more economical.

5. Toughness maintained in thin walled sections has made thin walled packages stronger and less susceptible to cracking.

6. Ability to laminate or preprint sheet has made unusual decorative and protective finishes possible.

Some limitations of the forming process which have restricted its growth are:

1. Before the forming process can be used, the proper sheet material must be available; therefore the additional cost of sheet manufacture must be considered as part of the cost of formed parts.

2. Formed parts must be trimmed, leaving a certain amount of trim scrap which must be effectively utilized to keep material cost low. Some materials cannot be re-processed so the trim must be sold at a loss; and in some instances the per cent of trim becomes excessive, making the process inefficient.

3. It is somewhat difficult to obtain sharp detail on the side opposite the mold, especially in thick walled parts.

4. It is impossible to produce thermoformed parts with abrupt changes in wall thickness as might be found with injection molded articles containing ribs or bosses.

5. It is sometimes difficult to obtain adequate material distribution in deep draws or sharp corners.

6. It is often difficult to eliminate slight markings or mold drag lines from positive male molds.

7. Only material capable of being trimmed without fracture can be considered acceptable for conventional operations. Materials of low elongation can be trimmed using special techniques.

8. The trimmed edge on formed parts can limit design possibilities and functional performance in certain parts.

II. The Forming Cycle

Nearly all thermoforming operations follow a set cycle regardless of the size of the end product. The cycle involves: (1) Heating the sheet or film, (2) forming the article, (3) cooling the formed item, and (4) trimming the part from the web. In some instances, the cycle is altered by cutting the sheet to exact size before forming. There are a number of ways each of these operations can be performed, the most popular techniques of performing these operations will be discussed briefly in the ensuing paragraphs.

A. Heating

Generally, thermoplastic sheet should be heated rapidly to forming temperature with a minimum temperature gradient through the sheet and from edge to center.*

* Some materials may prove exceptions, especially those which have been expanded to form a closed cell foam sheet. These should be heated slowly to prevent over-expansion of the cells and consequently collapsing of the sheet.

Factors effecting the heating time include:

1. Type and intensity of heat source.

2. Sheet temperature required for forming.

3. Absorption characteristics of the sheet.

4. Specific heat of plastic sheet.

5. Thermal conductivity of sheet.

6. Thermal degradation characteristics of sheet.

The degree of control necessary for proper heating will vary with the type of material and the amount of orientation induced during sheet manufacture. Materials with a wide softening range such as impact polystyrene do not require the same degree of temperature control as do materials with sharp melting ranges, such as polyethylene. Some plasticized materials require careful temperature control, since rapid or excessive heating can cause internal vaporization of volatiles or plasticizers with subsequent blistering or excessive exudation.

Most plastic materials tend to relax their internal strain or orientation during the heating cycle and the resulting movement of the sheet can cause thinning before the forming operation takes place. With conventional radiant heating equipment, sheets with excessive orientation should be avoided.

1. Radiant Heating - This is the most popular method of bringing plastic sheet to its forming temperature. As the term implies, the infrared rays emit or radiate from the heated source at temperatures ranging from 500°F to 1700°F. With thin transparent plastic materials, a considerable portion of the radiant energy may pass through the sheet without being absorbed. A reflecting shield placed on the opposite side will divert the energy back through the sheet. With opaque materials ten mils or greater in thickness, the radiant energy is almost entirely absorbed by the sheet. The effect of different pigments on heating time is less than might be expected, since the particles of pigment are completely surrounded by the plastic which tends to absorb the energy.

Most plastics are good insulators, so there is
danger of overheating the surface causing degra-
dation of material and possible color change before
the entire sheet is brought to the forming temper-
ature. Sandwich heating (heating both sides of the
sheet simultaneously) will minimize this possibility.
Further, sandwich heating has the additional ad-
vantage of substantially reducing the total heating
time. The distance between heater and sheet is
usually kept to a minimum to reduce edge losses,
although six or eight inches are considered a
practical minimum for rod or spot heaters if
localized heating is to be avoided.

2. Convection Heating - Convection heating in an air-
circulating oven is an excellent method of obtain-
ing uniform heat distribution and accurate temper-
ature control. Unfortunately, it is a much slower
process than radiant heating, but production may be
increased by heating several sheets at once. A
limitation to this method is the tendency of certain
materials to stretch or sag when allowed to remain
at their forming temperature for more than a brief
period. This limitation has restricted oven heating
to materials of high hot strength such as the acryl-
ics or ABS materials.

3. Conduction Heating - This is usually referred to as
platen or contact heating because the plastic sheet
is held in contact with a heated polished metal
surface. In one method the sheet is held between
two heated metal platens until the forming temper-
ature is reached and then is transferred to the
mold. In another method, the sheet is held against
a heated platen by air pressure until the forming
temperature is reached; then reverse air pressure
supplied through minute openings in the heating
platen is used to remove the sheet forcing it into
the mold. (See Figure 1)

B. Forming

There are many variations in the forming techniques.
Basically, all forming includes movement of the heated
plastic sheet by air (pneumatic) pressure, by mechanical
drawing or by a combination of these two techniques.
Air pressure may range from almost zero to several
hundred psi. In normal vacuum forming, atmospheric
pressure is utilized by evacuating the space between
the sheet and the mold which will give satisfactory

production of the mold configuration in the majority
of forming applications. When higher pressures are
necessary, they are obtained by sealing a chamber to
the top side of the sheet and building pressure within
by compressed air or steam. This system is referred to
as pressure forming and is usually necessary to obtain
fine detail with oriented materials or those of high
hot strength. It may also improve uniformity of ma-
terial distribution.

Essentially, vacuum and pressure forming are variations
of the same basic technique, even though the differences
in the formed parts may be significant. For convenience,
the forming techniques are sometimes discussed in terms
of vacuum forming with the understanding that pressure
forming could be adapted with only slight modifications
of equipment.

Mechanical stretching is often used to aid in material
distribution before the final forming by air pressure.
Stretching may be accomplished by drawing sheet over
a positive mold or by forcing it into a cavity with a
plug.

Sometimes when it is very difficult to obtain even ma-
terial distribution, the sheet is pneumatically stretched
into a balloon shape before it is stretched mechanically.
This gives a three step operations of (1) blowing a
balloon (2) mechanical stretching and, (3) forming to
the mold by air pressure.

A number of the various forming techniques will be
presented in relation to the degree of mechanical
stretching involved.

1. Straight Forming - The least complex technique is
    known as straight, or cavity, forming. The heated
    sheet is clamped over a cavity or mold box and pneu-
    matic pressures forces the sheet against the mold.
    A positive mold may be used inside a mold box.
    (See Figures 2 & 3) There are several character-
    istic features of parts made by straight forming
    into a cavity mold.

    a. The sharpest detail is on the outside of the
        formed item, i.e., the side next to the mold.

    b. The thinnest sections are in the corners at the
        bottom of the mold.

c. Parts with vertical walls or even slight under-cuts will release after forming, since the plastic shrinks away from the mold upon cooling.

d. Cavities may be placed close together in multiple molds without dangers of webbing.

Typical applications utilizing the straight forming process are blister packages, sundae dishes, some refrigerator door liners, and tote boxes.

2. Free Forming - In free forming the heated sheet is clamped over a mold box which is evacuated only slightly. This causes a blister or inverted dome to be formed without bringing the sheet in contact with the mold box except at the edges where it is clamped. If air pressure is used to balloon the material, this process is called free blowing. These techniques produce parts with exceptional surface finish and freedom from blemishes. Clear parts have excellent optical properties. The most representative application for this process is illustrated by airplane canopies, gun turrets and the like.

3. Drape Forming - Parts too deep to be successfully drawn in straight forming are often inverted and drape formed over either a positive or a combination mold. In this process, the heated sheet is mechanically pre-stretched over the mold before the sheet is formed by air pressure. At the completion of the mechanical stretching, the sheet is drawn over the edges of the mold platform to obtain the seal necessary to evacuate the space between the sheet and the mold. (See Figure 4)

Characteristic features of draped formed items are:

a. The sharpest detail is on the inside of the part, i.e., the side next to the mold.

b. The thickest section is on the top of the mold and the thinnest area is at the corners joining the mold side wall and base.

c. Drag or chill lines often appear on the side of the part, indicating a rapid change in the material thickness. This occurs because the sheet that first contacts the top mold surface is chilled and does not tend to stretch as much as the surrounding uncooled sheet. The chilled

sheet is usually drawn slightly during the remainder of the draping operation, so the drag line appears on the side a short distance from the top.

d. Positive molds used in drape forming must have a sufficient degree of wall taper to prevent the sheet from locking on the mold as the sheet shrinks during cooling. Rigid materials generally require greater wall taper than flexible materials, since the latter may br partially stripped from the mold if necessary. Parts with relatively straight side walls or those spaced close together will often have a web at the corners or bridge between parts. Webbing and bridging can generally be controlled by using a grid or ring assist. The rings are placed on the upper clamping frame and will act as individual drape frames, especially when multiple molds are used. These individual draped frames present bridging or webbing between molds. (See Figure 5)

Typical examples of drape formed items or combination draped and straight formed items are refrigerator door liners, tote boxes, display and advertising media.

4. Plug and Ring Forming - This method is a forerunner to drape forming and is usually accomplished by a draping action between die sections without additional pneumatic forming. The tooling consists of a positive mold and a ring or clamping frame which matches the contour of the mold base. The heated sheet is held in the ring and the mold is forced through the ring, drawing the sheet to the contour of the mold. Mold shapes are usually simple, so no further forming by air pressure is necessary. Molds are generally non-conductive to lessen chilling of the sheet during forming. (See Figure 6) There is relatively little plug and ring forming done today, although it may be suitable for forming certain types of housings in industrial applications.

5. Slip Forming - This is a variation of plug and ring forming using a slip ring which holds the sheet loosely. An oversize piece of sheet is placed on the spring loaded slip ring and as the ring is drawn over the mold, the material is allowed to slide through the ring giving it a drawing action.

The ring approximates the contours of the mold base so that after the drawing action, no further forming by differential air pressure is required. The process is limited to simple shapes made with materials of above normal hot strength.

6. <u>Snapback Forming</u> - Often a pneumatic pre-stretching of the sheet will aid in overall material distribution in drape or plug and ring formed parts. In snapback forming, the heated sheet is drawn slowly into a vacuum chamber to a predetermined depth by a slight differential pressure. Once the bubble has been drawn, the mold is brought down on the bubble until the edges of the mold seal on the box. The slight vacuum in the box is then released and the sheet is allowed to snap onto the mold. The mold is vented for air escape and the space between the mold and the sheet is sometimes evacuated to obtain better detail in the formed parts. The top of the mold must also be vented to prevent entrapment of the air. (See Figure 7)

7. <u>Reverse Draw Forming</u> - This technique uses nearly the same equipment as snapback, but the material distribution in the formed part may be very different. The major difference in the process is the reverse position of the bubble or ballooned sheet. In this case the heated air is introduced into the chamber and the sheet is billowed upward. The mold is then lowered into the bubble until it seals on the chamber, the pressure build-up in the billow chamber forces the sheet to conform to the mold shape. Again the mold must be vented and it may be evacuated if greater differential pressure is desired. (See Figure 8)

8. <u>Air Slip Forming</u> - This technique is similar in many ways to snapback forming, but the method of prebillow is different. The sheet is clamped to the top of a vertical wall chamber and prebillow is achieved by a pressure build-up between the sheet and the mold table as the mold rises in the chamber. The mold table is gasketed at the edges and essentially acts as a piston within the chamber wall. Upon completion of the stroke, the space between the mold and the sheet is evacuated and the sheet is formed against the mold by differential air pressure. (See Figure 9)

The most common application utilizing air slip is in the fabrication of refrigerator food chest compartments.

9. <u>Plug Assist Forming</u> - This technique combines many of the good features of both straight and drape forming and should give parts of uniform materials distribution which are easily removed from the mold. The heated sheet is clamped over the mold and the plug carries the sheet down into the cavity. As the plug enters the sheet, the air beneath the sheet is compressed, causing the sheet to billow up around the plug, the blowing action prevents the sheet from contacting the cavity lip as it is drawn into the cavity. The plug stops near the bottom of the mold, the mold is evacuated, and the sheet is transferred from the plug to the mold by differential air pressure. Once the part is formed, the plug may be removed from the mold. (See Figure 10)

It is best to restrict the area of sheet which is sealed against the mold, this allows more definite control of the forming operation and eliminates any differences in sheet area used for the center or edge cavities and multiple molds. Usually an area greater than the exact projected area of the part is used, since material between the cavities can be carried into the mold and contribute to the side wall.

Among the most important aspects of plug assist forming are the variables relating to the plug. The size of the plug is usually about 70% to 90% of the cavity volume, regardless of the size of the cavity involved. This means the clearance between plug and cavity increases with an increase in part size. The plug conforms to the general contour of the cavity although it is usually left smooth and undetailed. The radius between bottom and side wall approximates that of the container and may be quite sharp for small containers. The radius on larger plugs is usually more generous, even though the corners in the mold have a small radius.

Plugs are often made of conductive material such as aluminum so they may be temperature controlled. These plugs should be kept as hot as is consistent with good performance, since elevated temperatures aid in maintaining sheet temperatures and prevent uni-directional orientation. Plug temperatures can also be used to help control material distribution in the formed part.

In many cases by heating the plug to about the form-
ing temperature of the material, a partial sticking
of the material to the plug will occur, thereby allow-
ing an excess of material to be carried into the lower
portion of the cavity. By carefully controlling the
depth of penetration, the excess material on the base
of the plug can be distributed quite uniformly over
the bottom of the mold as it is drawn off the plug
and into the cavity.

A non-conductive plug may be used in most appli-
cations. It does not offer as much control as
the heated plug, but is less expensive and will
often perform satisfactorily. These plugs can be
made from a variety of materials, including thermo-
setting plastic resins or straight grain hard woods
of low pitch content, such as mahogany, hard maple
or birch.

The speed of plug penetration will effect material
distribution and drag lines. Generally, the fastest
plug possible should be used to stretch the sheet
while it is still hot to eliminate any drag lines.
Slower plug speeds will often result in drag lines
where the material first touches the plug or is
stretched over the mold lip. Adequate platen pres-
sure should be available to minimize any plug slow-
down or hesitation as it enters the sheet, since a
significant change in plug speed can leave a double
drag line on the formed parts.

The plug is usually allowed to penetrate nearly to
the bottom of the cavity. If the other variables
are properly controlled, this should give optimum
material distribution, in certain cases it is only
practical to lower the plug to some point beyond
the half-way mark. This compromise may be necessary
when it is impossible to prevent the material from
dragging over the lip of the cavity. In most cases,
the depth of plug penetration will be determined by
the plug temperature and the thickness of the bottom
required.

Properly controlled, the billowing should take place
from the start of the plug movement into the sheet
until the plug is stopped. The pressure build-up
causing billowing is created because the air in the
mold cannot escape through the vent holes as fast
as it is displaced by the plug. The amount of billow-
ing is controlled by (1) the area of sheet clamped

to the mold (2) plug speed (3) ratio of vent openings to container volume and (4) the differential pressure across the vent openings. Greater plug speeds mean more rapid compression and displacement of the air in the mold and increased billowing. Increasing the number or size of vents will allow the air to escape from the mold more readily and decrease billowing. If the vacuum line is partially opened as the plug enters the cavity, the differential air pressure across the vent holes will increase, allowing the air to escape from the mold more rapidly. With most production molds there is likely to be excessive pressure build-up during the rapid plug penetration, so it may be necessary to increase drastically the number of vent holes and install a vacuum bleed-off line which bypasses the main vacuum shut-off valve. This bleed-off should have a regulating valve which is timed to open as the plug enters the sheet. (See Figure 10)

Plug assist forming is the most commonly accepted method of fabricating deep parts such as hot drink cups, dairy containers, and refrigerator door liners to a lesser degree.

10. Plug Assist-Reverse Draw Forming - For the forming of large area deep drawn parts it is often advisable to precede plug penetration with a pressure build-up beneath the sheet causing it to balloon upwards. This ballooning tends to eliminate any heavy section which might occur in the center of the bottom. It also makes the load build-up on the plug more gradual, which tends to lessen any sudden change in plug speed as it enters the sheet. (See Figure 11)

11. Air Cushion Forming - This is another variation of plug assist forming in which air is introduced through the plug as it enters the sheet. This technique tends to reduce any sticking or dragging which might occur between the sheet and the plug as it enters the cavity. This process is also intended to improve material distribution, especially by eliminating a heavier section across the bottom of the plugs used for large area parts. These two latter forming methods are being used extensively by the appliance industry to form items such as refrigerator food compartment chests, washing machine tubs and the like.

12. <u>Plug-Assist Air Slip Forming</u> - It is often bene-
    ficial to combine forming techniques to achieve
    improved material distribution in complex parts.
    The plug-assist air slip combination would appear
    ideal for forming high ridge positive shapes with
    deep cavity sections such as most refrigerator
    inner door liners. With this technique, the sheet
    billows upward as the mold rises. Just before the
    upper ridge of the mold strikes the bubble, the
    plug is introduced from the top, reshaping the
    bubble to accommodate the mold ridge and at the
    same time carrying material into the cavity sections.
    If properly controlled, the material may be uniformly
    distributed before it contacts the mold. (See Figure
    12)

13. <u>Matched Die Forming</u> - This may be regarded as a con-
    tinuation or final stage of plug-assist forming.
    As the term implies, a pair of matched molds form
    the softened sheet and no additional air pressure is
    needed. The dies are designed to allow for the thick-
    ness of material remaining after forming. The dies
    or molds are normally mounted on press platens, the
    softened sheet is placed on the open mold, and the
    mold is closed to form the part. If the dies are
    made of a hard material such as metal or a thermo-
    setting plastic, close alignment during forming is
    required to keep the dies properly matched. Often
    one die surface is of the softer material such as
    foamed rubber, which is not cut to an exact contour
    but simply forces the sheet to conform to the oppo-
    site die face. This modification requires less
    critical alignment during die movement. (See
    Figure 13)

C. <u>Cooling</u>

The time required to cool formed parts may be the longest
phase of the entire forming cycle and as such deserves
careful consideration. Parts may be cooled from the mold
side by conduction and from the opposite side by con-
vection. To obtain maximum cooling through the mold it
is necessary to use mold materials with high thermal con-
ductivity. When such molds are properly cored for temper-
ature controlled water, most of the heat is moved through
the mold. The rate of heat transfer decreases as the part
cools due to a decreasing temperature differential. In
cavity formed parts, the cooling rate is further retarded
because the sheet tends to shrink away from the mold,
thereby losing surface contact for conduction.

With temperature controlled molds there is a tendency
to hold mold temperatures below 100°F to shorten the
cooling phase. This rapid cooling and the resultant
induced thermal stresses can cause a reduction of
physical properties in the formed part. To avoid this,
all temperatures over 130°F should be used. It may be
necessary to operate molds at 170°F or higher to obtain
optimum parts even though the cooling cycle is increased.
Additional cooling from the top side can be achieved with
fans or blowers. These are especially needed when non-
conductive molds of wood, thermosetting plastic, or
plaster are used. Water sprays are generally not rec-
ommended as they usually cause spotting of the surface
of the part.

Parts may be removed from the mold when they are cool
enough to prevent warpage. Usually the formed part is
released from the mold by building up air pressure under
the part. Once the part is released, the clamping frame
is raised or the mold is lowered to separate the item
and the mold. When parts are draped over molds of in-
sufficient wall taper, or where there are undercuts,
it may be necessary to strip the part from the mold.
This may be accomplished by ejection pins or rings
mechanically actuated from within the mold. Another
method is to build a light grid or framework onto the
clamping frame. The sheet is placed on top of this
grid. After the parts are formed and the clamping frame
and mold are separated, the grid work assists in strip-
ping the formed parts from the mold. Once the formed
parts are removed, they may be placed in jigs or racks
for further cooling or, in continuous forming, they may
be fed directly into a trimming press.

1. Shrinkage - During the cooling phase there is con-
   siderable shrinkage of the formed item due to both
   thermal contraction and changes in density which
   accompany crystallization of the material. Most of
   the shrinkage takes place by the time the formed unit
   has reached room temperature; however, the following
   15 to 30 minutes will usually produce further notice-
   able shrinkage. After 30 minutes most material will
   continue to shrink very slightly over an extended
   period of time. This continued shrinkage is especially
   prominent in crystalline polymers such as the poly-
   olefins and saran when they have been somewhat super-
   cooled after forming. If close tolerances on formed
   parts are to be maintained, the time interval between
   forming and trimming must remain constant. This timing
   becomes less critical as the interval between forming
   and trimming increases. If parts are to be trimmed
   shortly after forming, the remaining shrinkage must

be considered in calculating outside dimensions of the part. If possible, the safest procedure is to maintain an inventory of formed parts which are not trimmed for at least 15 minutes after forming. If this is done, slight variations in time between forming and trimming will not noticeably change the overall trimmed dimensions.

The shape of the mold also affects the amount of shrinkage during cooling. In cavity molds the parts shrink away freely from the mold and maximum shrinkage occurs. With positive molds, especially those with inadequate wall taper, the part is restricted by the mold and shrinkage is somewhat hindered. Parts formed on combination molds can have slight variations in their shrinkage patterns. For this reason, parts will often vary from the theoretical shrinkage values given for different materials.

D. Trimming

Trimming generally involves a separate operation and a subsequent additional investment in equipment. The method of trimming will be determined by the type of plastic, the location of the trim line, the thickness of the sheet, and the quantity of parts to be trimmed. On comparatively short runs, parts may be trimmed along nearly any desired line using band or circular saws, manually or mechanically operated shears, shapers, or routers. If additional finishing of rough edges is desired, a wet or dry continuous belt sander may be used.

For longer production runs, cutting or shearing dies mounted in a press are most commonly used. Cutting dies, such as steel rule dies used extensively for scoring paper boxes, are popular for trimming plastic sheet up to approximately .050 inch thickness in production runs usually under 100,000 strokes. These dies are mounted either in an inclined mechanical press or in an upright mechanical clicker press. The dies usually cut against a softer material such as hardwood or brass. Heavier machined cutting dies referred to as high dies or clicker dies may be used to cut heavier sheet for extended production runs. (See Figure 14)

Matched shearing dies can be used with a wide range of sheet thicknesses from under 5 mils to over 200 mils for most materials. The tolerances between punch and die are much closer than are commonly used for sheet metal of the same thickness. For impact polystyrene a range of two to five per cent of sheet thickness is considered

proper clearance between punch and die. Plastics usually tend to bend and break rather than shear unless a retaining clamp is used opposite the punch or die or both. These dies may be mounted in a pneumatic, hydraulic, combination hydraulic-pneumatic presses, or mechanical presses. A positive shearing action without hesitation seems to give the cleanest cut, so the mechanical presses seem particularly well suited for shearing dies. (See Figure 15)

Dies may be single or multiple units depending on the size and capacity of available trimming presses and the production rates required. Normally when cut sheet is used the trimming die will match the forming mold.

One characteristic common to both cutting and shearing dies is the flange on the formed part. When close die alignments are maintained, the flange may be as small as .005 inch. In some cases the flange can be completely eliminated by intentionally distorting the part while it is being trimmed.

Another technique, referred to as planetary trimming, allows the parts to be trimmed on the side wall leaving no flange. The advantages of this method are relatively low die costs and close spacing in multiple molds. Relatively little power is required, since the trimming is done by a simple shearing operation with very uniform loading throughout an extended cycle. The die consists of two flat plates, one stationary and the other capable of moving eccentrically in a circular path. The part is placed between the upper and lower plate. As the upper plate moves around the periphery of the formed article, there is a shearing action between the two plates. (See Figure 16)

For some applications it is desirable to trim the formed part while it is still in the forming mold. One such method of trimming-in-place which appears feasible incorporates a knife edge around the periphery of the forming die and a movable heated ring directly over the die. After the object is formed in the conventional manner, but before it is cool, the heated ring drops down and presses against the knife edge in the mold and pinches the part from the web. The process may also work in reverse by placing a heated knife edge on the upper platen and bring it in contact with the sheet against a flat mold surface. The problem with this method is that plastic may build up on the trimmer and reduce its effectiveness.

Another method used is shearing dies which either punch a section of sheet that is then carried into the mold and formed, or which trim the finished part before it is removed from the mold. These techniques are more involved and require expensive tooling.

III. Forming Equipment

A. Machine Components

The equipment for sheet forming can be built up from basic components to any desired degree of completeness. A simple machine capable of straight forming only would have (1) heater, (2) vacuum pump, (3) accumulator tank, (4) vacuum line and valve, (5) mold table, and (6) supporting framework including sheet clamping frame. Many forming machines have advanced far beyond this elementary stage and are capable of production operation with automatic cycle control using a variety of forming techniques. Such machines would have additional features of a movable lower platen or clamping frame, a movable upper platen, movable heaters or sheet carriage, air pressure systems for preballooning sheet and ejecting formed parts, vacuum bleed-off systems for control of ballooning during plug-assist or air-slip forming, and necessary controls for each component of the system.

B. Machine Types

Superimposed on these essential elements is a wide variety of materials handling devices for loading and unloading sheet or indexing roll stock and moving it through various phases of the forming cycle. These machines may even be further combined with equipment for trimming and other packaging features such as product loading and heat sealing to a paper backing. Such machines are often classified by their methods of materials handling or by the number of operations they can perform simultaneously.

A single stage type of machine is one which can perform only one operation at a time and its total cycle will be the summation of times for loading, heating, forming, cooling and unloading. (See Figure 17)

Most single stage machines operate from sheet stock; however, some models are equipped with a roll feed mechanism which indexes the roll stock after each complete forming cycle. These roll feed mechanisms will eliminate most loading-unloading labor, and in one sense these machines may be considered continuous. Any material may be

used which is flexible enough to be rolled on a core.
Heavier sheet can be roll fed if heaters are used to
soften the sheet as it unrolls. (See Figure 18)

A special variety of single stage machine is one capable
of contact heating and pressure forming. Most materials
may be formed by this machine although it is especially
well suited for use with oriented polystyrene. One type
is fed from precut discs, while another is fed from roll
stock. These machines are particularly well suited for
preprinting and detailed forming of shallow articles,
such as container lids.

A double stage machine as the name implies performs two
operations simultaneously. Such a machine usually con-
sists of two forming stations and a set of heaters which
will move between stations. (See Figure 19)

The three stage machines are usually built on a horizon-
tal circular frame and is referred to as a rotary machine.
Here loading-unloading, heating, and forming-cooling are
performed as simultaneous operations with the machine
indexing 120° after each operation. Such machines are
used extensively for sizeable production runs on large
area parts, such as refrigerator inner door liners,
food chest compartments and the like. (See Figure 20)

A fourth stage may also be added to accommodate a trim-
ming press. The circular frame then would be divided
into 90° segments.

Another machine playing an important part in the growth
of the thermal forming industry is the continuous form-
ing machine. This type is primarily designed for high
volume operations and seems particularly well suited to
the packaging industry. Such a unit may be operated
directly from an extruder or from roll stock since the
sheet movement is continuous at a constant speed. The
sheet may retain its heat from the extruder or addi-
tional heat may be added, especially for roll stock, by
passing the sheet through a heating section. There are
two types of continuous forming units. One type utilizes
conventional molds which travel horizontally at the same
speed as the sheet. The second uses a rotating cylinder
as the mold and is often referred to as a drum former.

With the horizontal unit, the sheet is clamped at the
edges and moves at a controlled speed. The mold and
plug table move with the sheet, but have a reciprocating
motion so they can index to the next unformed section of

sheet once the forming cycle is complete. This type of unit is suitable for any of the common forming techniques. (See Figure 21)

The drum type former uses either flat or curved mold sections attached to a rotating cylinder. The sheet is held only by the edges or is simply draped over the drum, unless a special indexing clamp frame is used for each row of parts. The hollow center of the cylinder must be sectioned so vacuum can be applied at a fixed position in the mold as the drum rotates. With straight walled cavity molds, it becomes increasingly difficult to strip the web from the mold as the drum diameter decreases. To avoid a binding action on such parts they must be trimmed individually or in rows before being ejected from the mold. (See Figure 22)

C. Molds

Certainly one of the advantages of sheet forming is the variety of materials which can satisfactorily be used for molds. Those used for vacuum forming need only withstand 14 psi and as such require a minimum of strength. If pressure forming is used, molds must resist up to about 300 psi without deflection. The wear on the molds is negligible, since there is little flow of the plastic material against the mold surfaces.

For vacuum forming, many materials are available for mold manufacture, including wood, plaster, thermosetting plastics and metals. Wood and plaster are usually limited to short runs or sample preparation since they tend to chip and break with extended production. Plastic molds are also used for short runs and sample preparation because they are easily molded. However, these materials have sufficient strength for most extended production runs. The major difference between plastic and metal for production molds is the difference in thermal conductivity of the two materials.

1. Mold Construction - Typical molds for forming will have a series of vent holes located in those areas where the sheet will be formed last. In vacuum forming they project downward into a common chamber at the bottom of the mold.

In constructing molds there are a few fundamentals which should be observed.

a. If possible avoid flat surfaces, since a slight dome or dish effect will allow the sheet to stretch over the entire surface avoiding minute bumps which sometimes appear in these flat sections.

b. Maximum allowable vent hole diameters will vary with materials and sheet thickness. For impact polystyrene in thicknesses greater than .060 inch, holes up to .030 inch in diameter may be used. For thinner sheet, especially where both sides of the part will be seen, it may be necessary to reduce the hole diameters to .010 inch to avoid any hole marks. Polyethylene formed parts exhibit more severe hole marking, so it is usually necessary to hold the diameter under .020 inch regardless of the sheet thickness and at .010 inch for thinner gauges. Often it is possible to split molds, leaving a .010 to .015 inch wide slot which may extend around the entire part. The slot will allow greater passage of air and will exhibit no more of a vent mark than a hole of comparable diameter.

c. To minimize restrictional flow through these openings, the holes should be back drilled to approximately .01 inch from the mold surface or closer if possible. (See Figure 22)

d. The number of vent holes will depend on the desired rate of drawing. It is suually desirable to form as rapidly as possible, so an ample number should be provided. With a combination mold which has several cavity sections, as in a refrigerator door liner, it may be desirable to increase the ratio of holes to chamber volume to evacuate a deep chamber more rapidly than an adjacent shallow section. Rapid plug-assist forming will require an appreciable increase in the number of vent holes.

e. Holes should be located in those areas into which the sheet will be drawn last. In parts where fine detail or textured patterns must be accurately reproduced, vent holes less than one-half inch apart may be necessary.

f. Whenever undercuts are involved, there are five basic techniques used to aid in removal of the parts from the molds. (1) Split section molds may be disassembled to remove the part from the mold. (2) Hinged sections which unfold as the part is removed may be used for straight line undercuts. (3) Mechanical strippers built into

the mold may be incorporated to provide positive
mold release for parts with slight undercuts,
especially in high speed production operations.
(Example - production of containers designed to
accommodate snap-in lids). (4) Protruding
sections which are cam-actuated may be withdrawn
into the mold before the part is removed. The
cams are usually actuated by air cylinders mounted
within the mold base. (5) A portion of the mold
may be built so it is easily removed and remains
as an orphan insert in the finished part. Such
inserts are held in place by an undercut. If
possible they should be made from the same ma-
terial used in forming the part so there will be
no difference in the thermal expansion and con-
traction because of temperature change. (See
Figure 23)

g. Production molds should be cored so temperature
control water can circulate freely through the
mold base. For combination molds with high
ridges it is often advisable not to core these
ridges completely so the upper section will
operate at a higher temperature than the re-
mainder of the mold. Where tubing is cemented
to the bottom of the mold, there are few prob-
lems of leaks between the vacuum chamber and the
cooling system. If the molds are cored for water,
careful planning is required to assure proper
vacuum channels. Usually such molds are built
with alternate channels for air and water or
with an upper and lower section. The upper
section contains channels for water and the
lower section a vacuum chamber. The vacuum
holes are then drilled through the casting in
areas that are not channeled and connected to
the vacuum chamber. (See Figure 24)

2. Design Considerations - Parts should be as free as
possible from stress concentration or susceptibility
to stress during normal use. Design will play a major
role in minimizing stresses.

Parts must be designed with a fabrication technique
in mind. The choice usually involves a compromise
between the most favorable technique and limitations
of available equipment. Once chosen, the fabrication
method will set certain limits on the part design.

Parts formed over positive molds must have ample
wall taper for release from the mold. Generally,
three degrees are minimum for side wall draft. As
the distance across the top of a positive mold in-
creases, the total shrinkage is greater, so it is
preferable to increase the degree of wall taper to
allow the formed parts to slide readily up on the
side walls as they cool and shrink.

Sharp corners cause stress concentration, so the
largest possible radii and fillets are desirable.
With some materials it is difficult to draw sheet
into corners where the radius is less than twice
the sheet thickness.

Avoid notches or square holes when punching formed
parts. Round holes are best and are preferable to
oval holes for minimizing stress concentrations.

Ribs may add rigidity to formed parts when placed
parallel to the direction requiring greater rigidity.
Generally, several small ribs are superior to one large
rib as the greater distance from the neutral axis to
the outside surface will build up greater stress.
If a formed part must flex a predetermined amount
because of excessive loading, it is often best to
eliminate all ribs so the part may flex easily with
a minimum internal stress build-up. Proper design
usually calls for a balance between stiffness and
flexibility and the load should be distributed through-
out the part rather than on a single flange or rib
section.

Often it is necessary to stack formed parts together
with controlled spacing between units. When such parts
are allowed to jam together, a wedging action can induce
high stresses within the part and cause them to split.
To avoid this jamming and to control the space between
parts, a stacking boss or shoulder may be incorporated
in the part. This boss consists of a vertical or
undercut portion on the side wall which will interfere
with a similar section in the unit above or below
when placed in a stack. It is necessary to form such
bosses distinctly and have a sharp break at the bottom
and top of the vertical section. The height of the
stacking boss must be greater than the vertical cross
section of the formed unit at the point of least taper.
Otherwise tapered walls will interfere before the stack-
ing sections engage each other. These sections may be
placed at the top or bottom or anywhere along the side
wall of the formed unit. However, the container must

be rigid enough in this area to prevent the bosses
from deflecting and allowing the units to jam.
(See Figure 25) Stacking bosses are most critical
when used in packaging work, especially on formed
containers which must be made to run on automatic
vending or dispensing equipment.

IV. Summary

It has been the object of this paper to present a brief,
but fairly complete idea of some of the applications which
can be best served by the various thermoforming processes.
While a number of forming techniques were discussed, it is
probably safe to say that today the majority of applications
utilize the following techniques; straight, drape or combina-
tions of these or plug assist with any of its modifications.
With continuing developments in sheet materials, machines,
and manufacturing techniques there is no reason to believe
that the forming industry will not play a major role in the
continued growth of thermoplastics industry.

J. R. Lynch
9-12-60
al

Figure 1

CONTACT HEATING
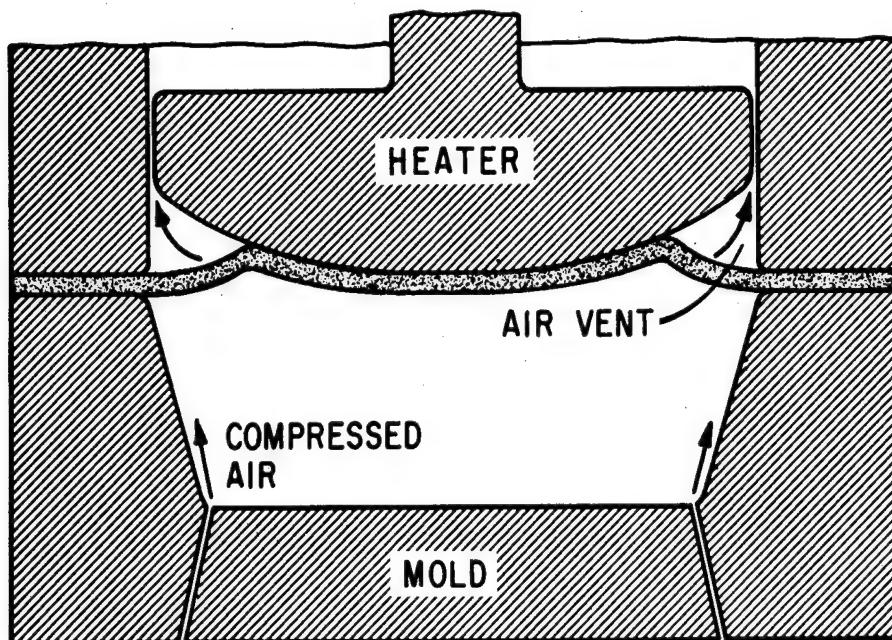
Figure 2

STRAIGHT FORMING - VACUUM
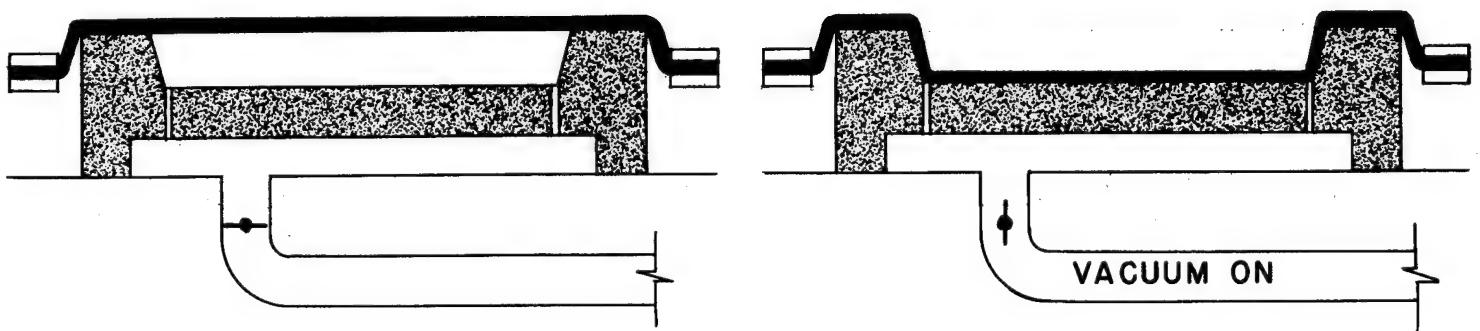
Figure 3

STRAIGHT FORMING – PRESSURE

COMPRESSED AIR OPEN

VENT HOLES

Figure 4

DRAPE FORMING

VACUUM ON

PRESTRETCH ▶ FORM
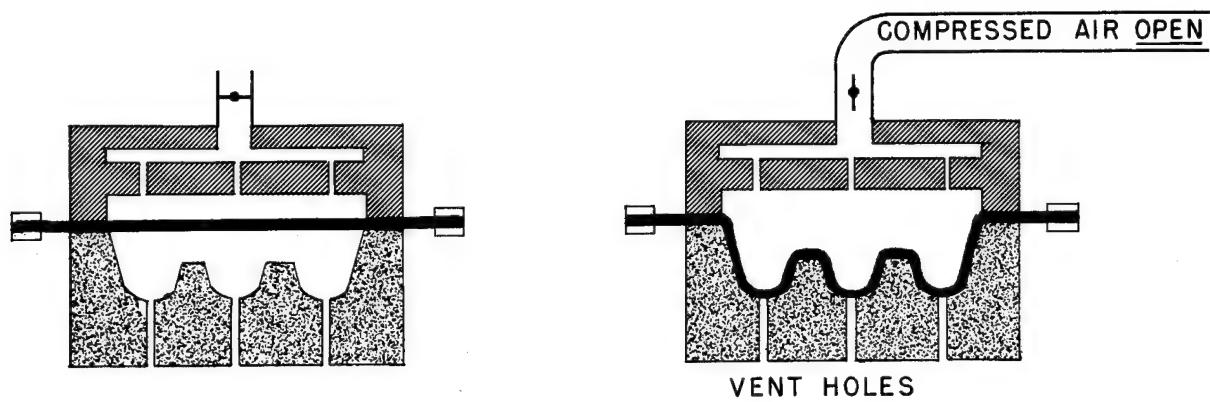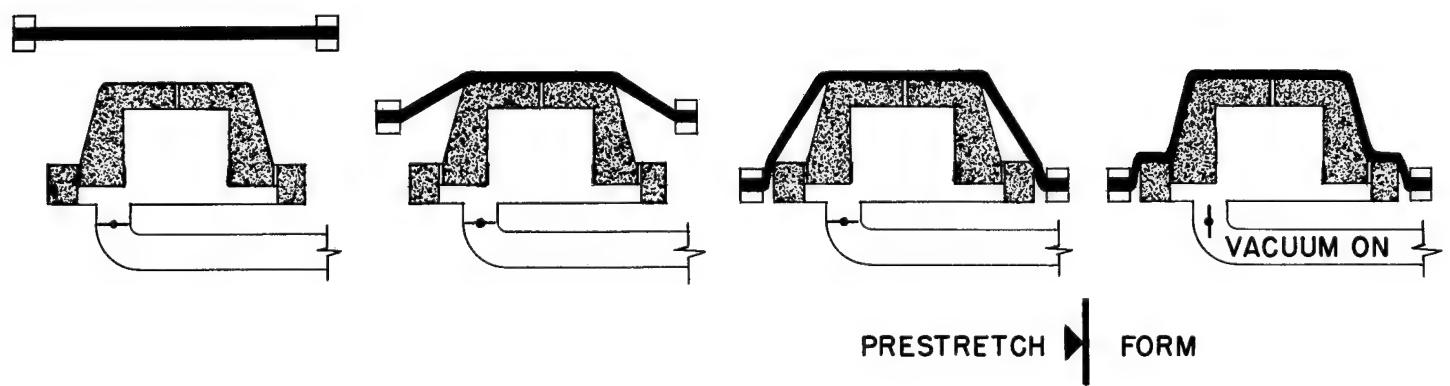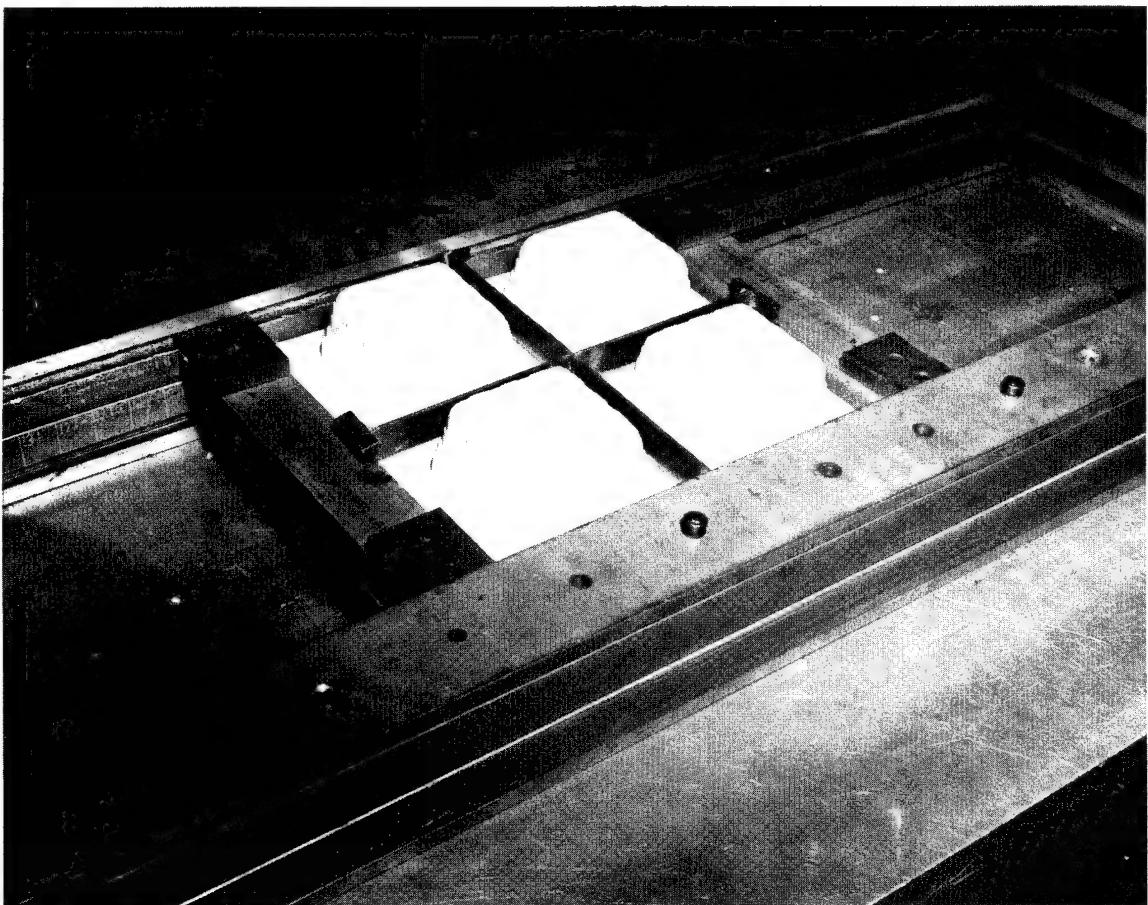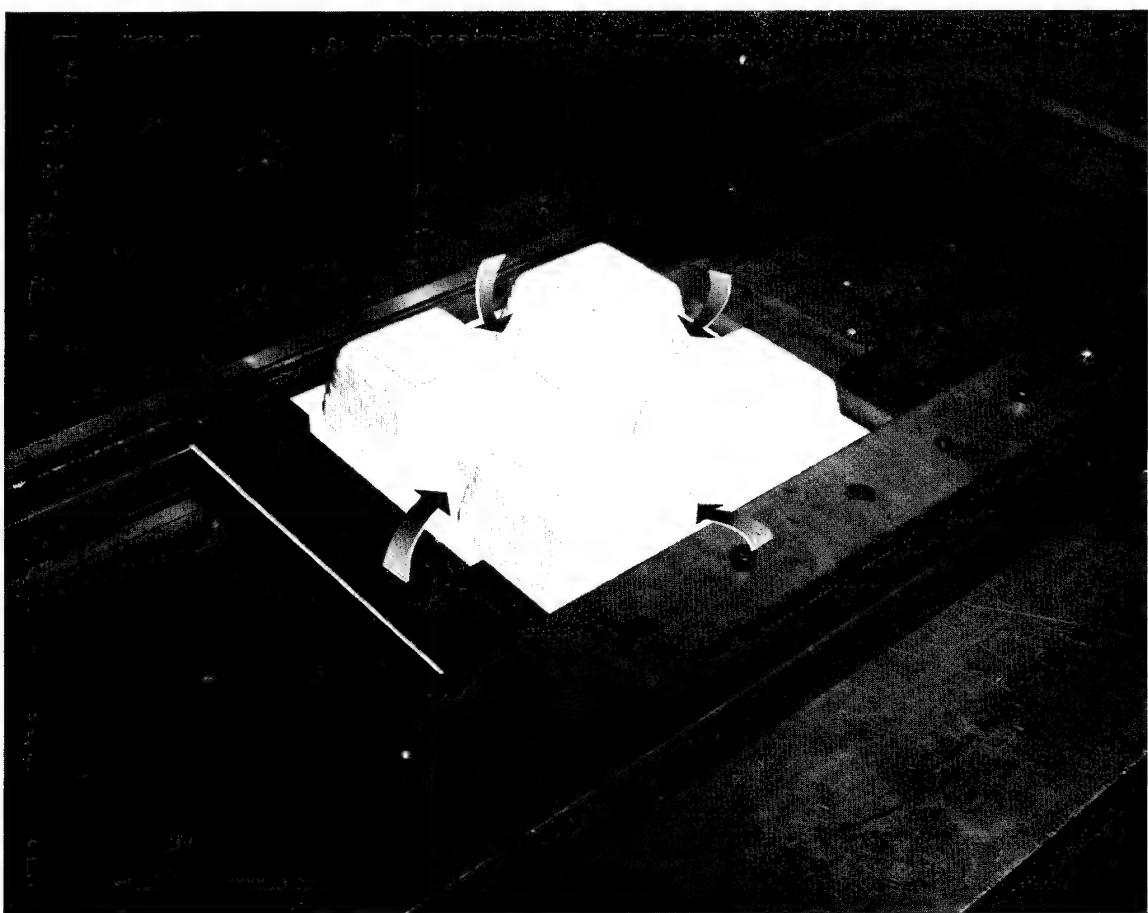
Figure 5

Figure 6

PLUG AND RING FORMING
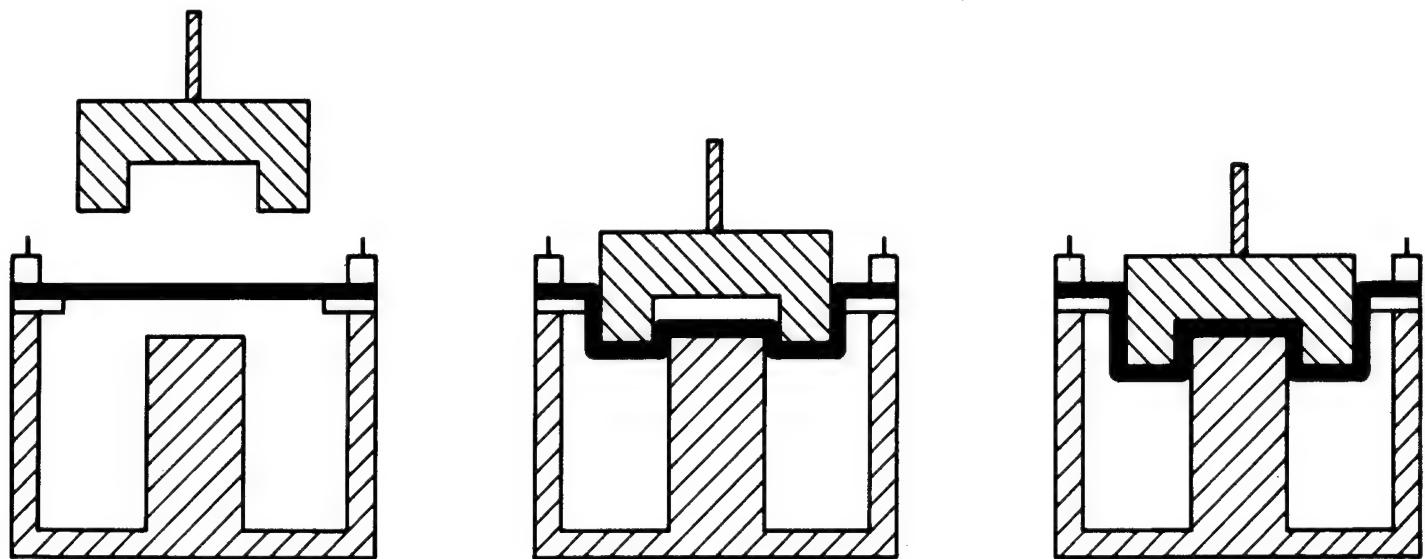
Figure 7

SNAPBACK FORMING

VACUUM ON

SLIGHT VACUUM

AIR OPEN

PRESTRETCH ▶ FORM
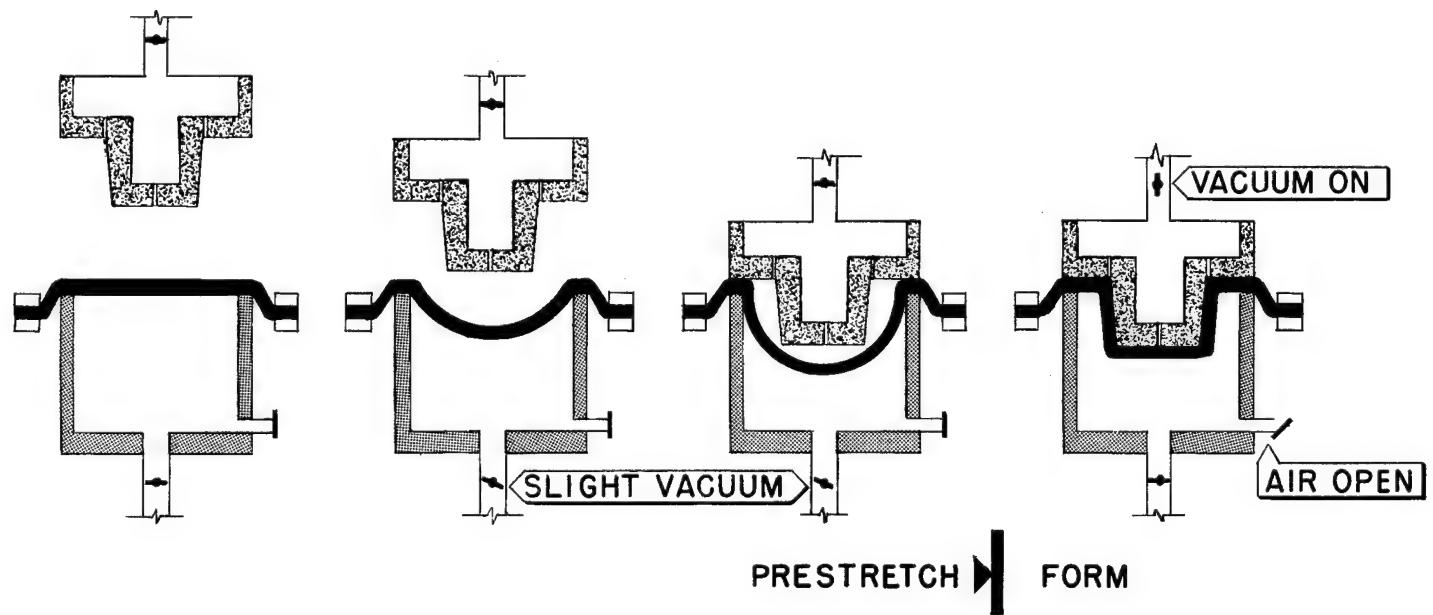
Figure 8

REVERSE-DRAW FORMING

SLIGHT
AIR PRESSURE

SLIGHT
AIR PRESSURE

VACUUM ON

SLIGHT
AIR PRESSURE

PRESTRETCH ▶ FORM
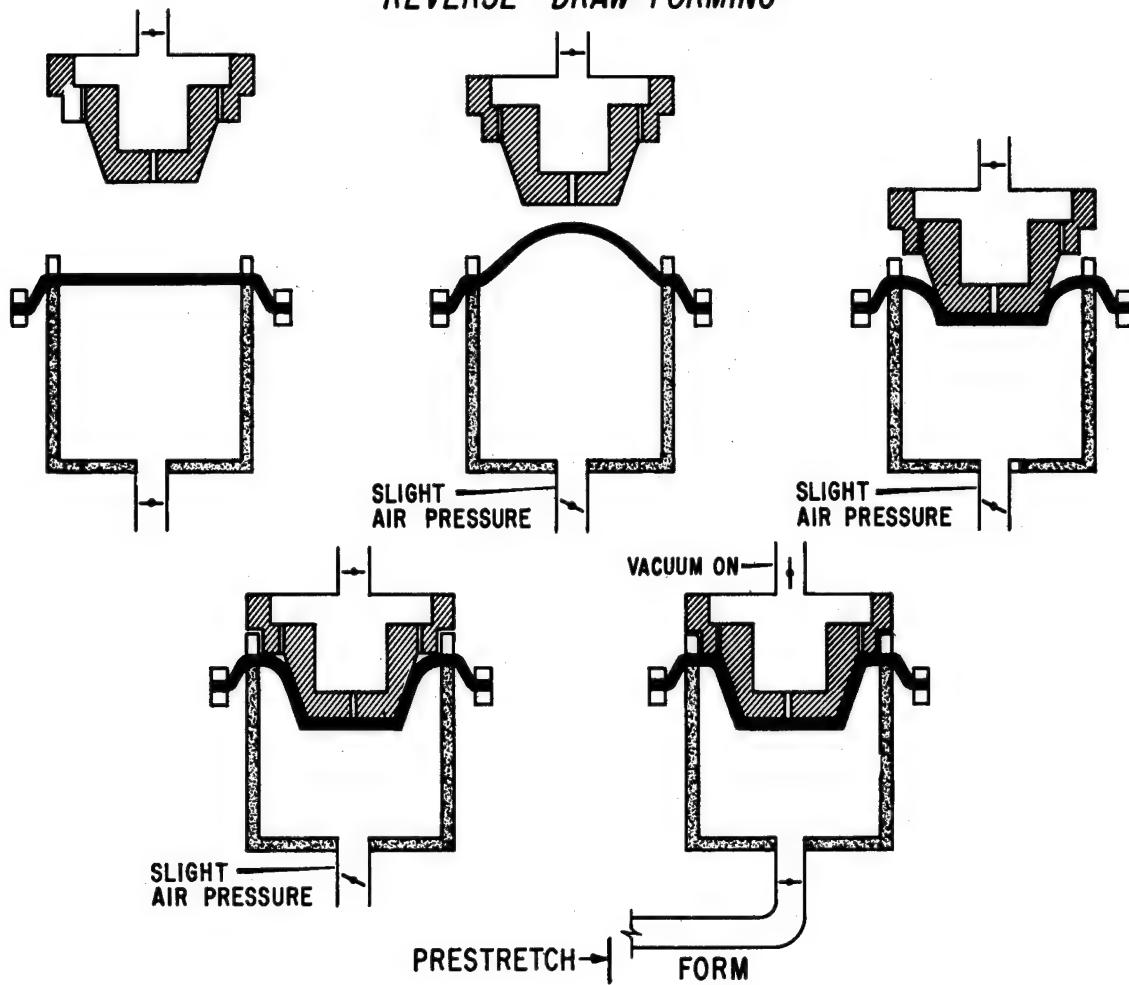
Figure 9

AIRSLIP FORMING

VACUUM ON

PRESTRETCH ▶ FORM

Figure 10

PLUG-ASSIST FORMING

PRESTRETCH → | FORM

VACUUM ON
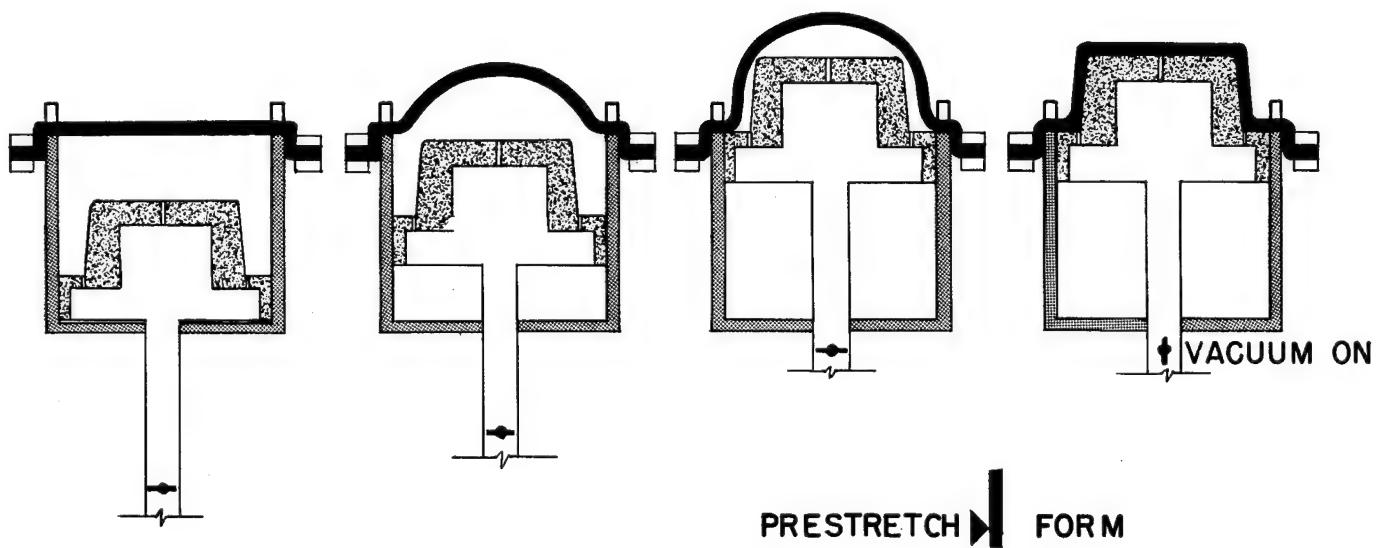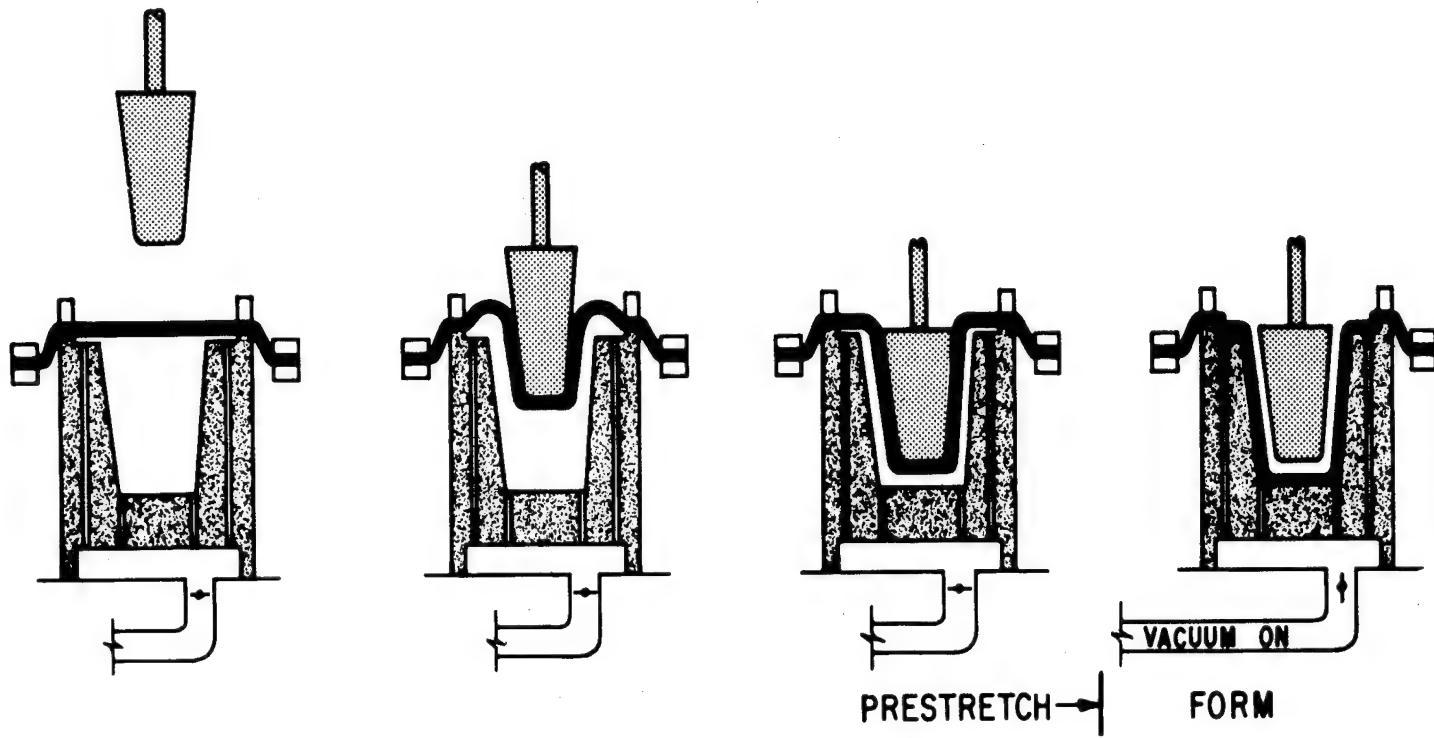
Figure 11

PLUG-ASSIST — PRE-BLOW

SLIGHT AIR PRESSURE

VACUUM BLEED

VACUUM BLEED

FULL VACUUM ON

PRESTRETCH → | FORM
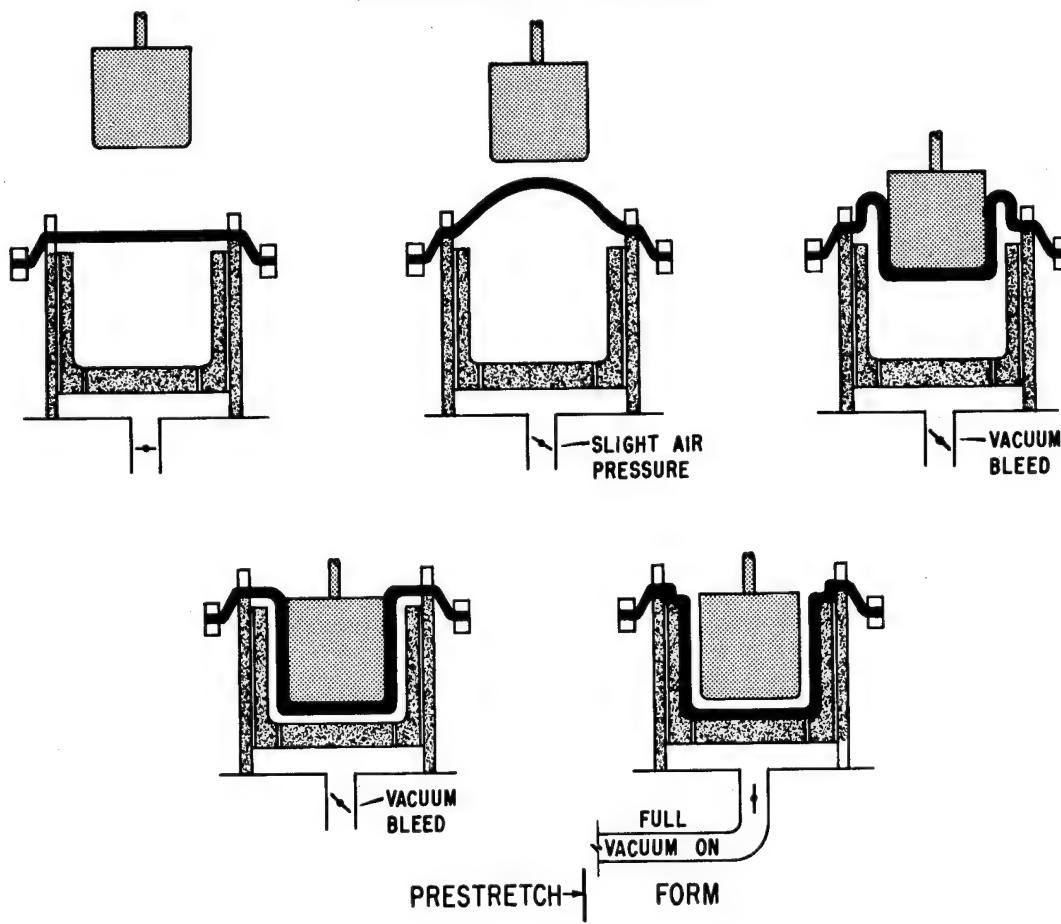
Figure 12

AIRSLIP-PLUG-ASSIST COMBINATION
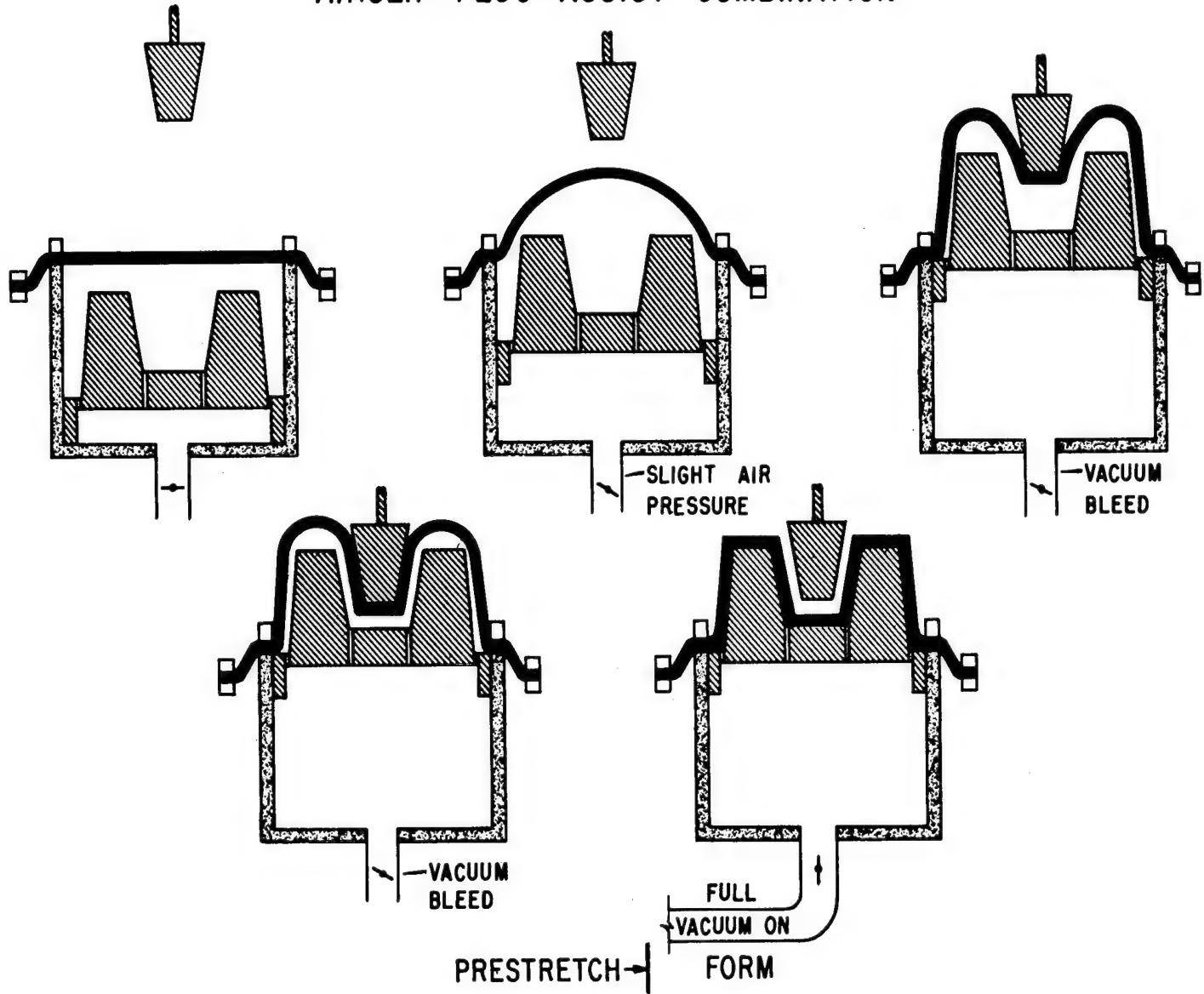
Figure 13

Matched Die Forming

Female Die

Press

Heater

Plastic Sheet

Sheet Clamp

Male Die

HEATING

Matched Die Forming

Press

Forming Plastic Sheet

Female Die

Heater

Sheet Clamp
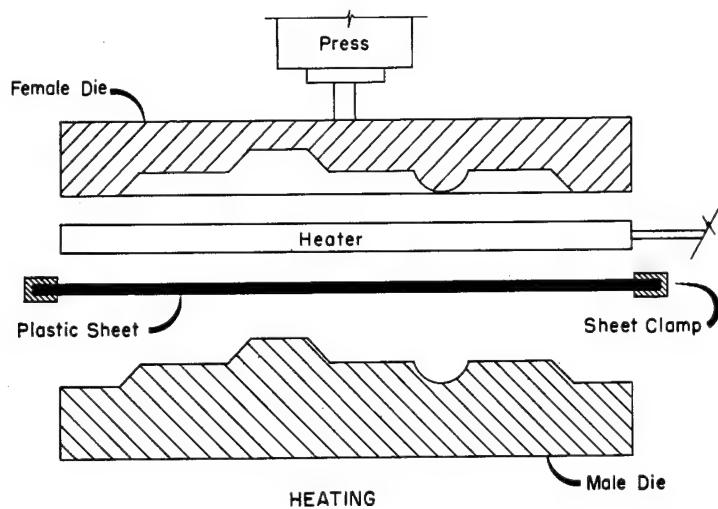
Male Die

FORMING

Matched Die Forming

Female Die

Press

Heater

Formed Sheet

Sheet Clamp

Male Die

REMOVING PART

Figure 14
CUTTING DIES

CLICKER DIE

STEEL RULE

PLASTIC, WOOD OR METAL
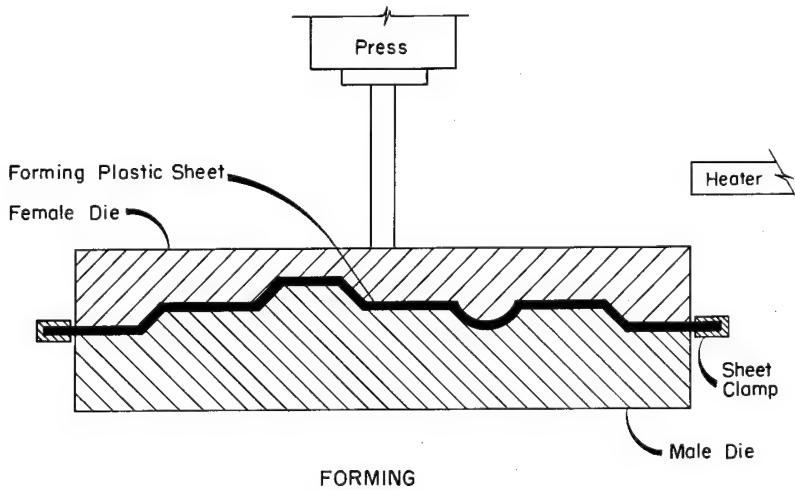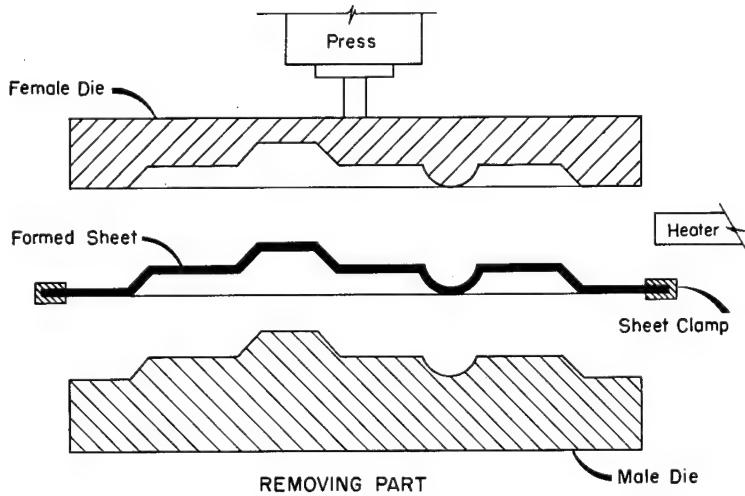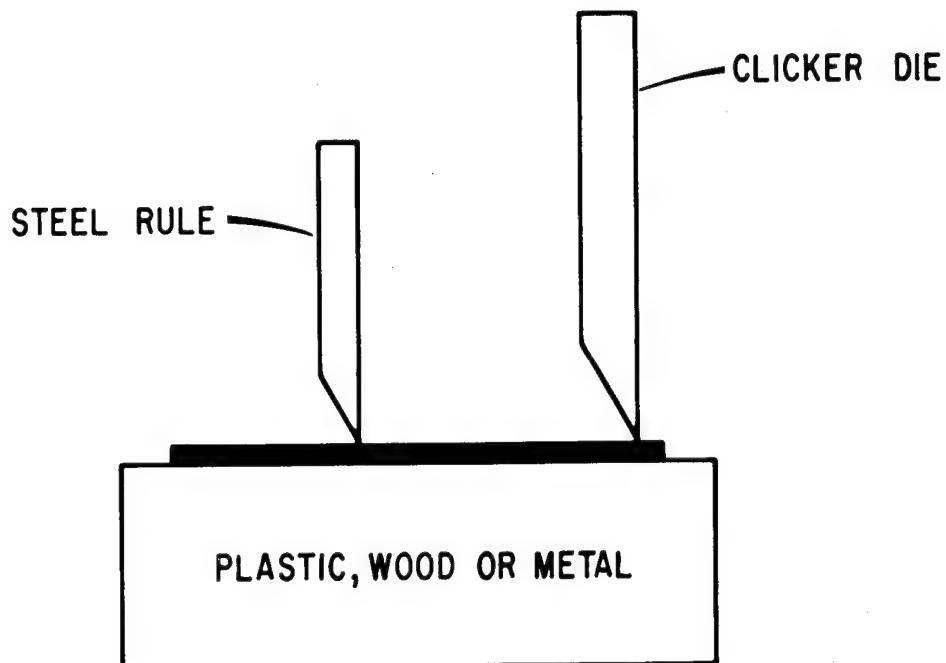
Figure 15
SHEARING OR BLANKING

STRAIGHT PUNCH

CHAMFERED PUNCH

SPRING LOADED

SPRING LOADED
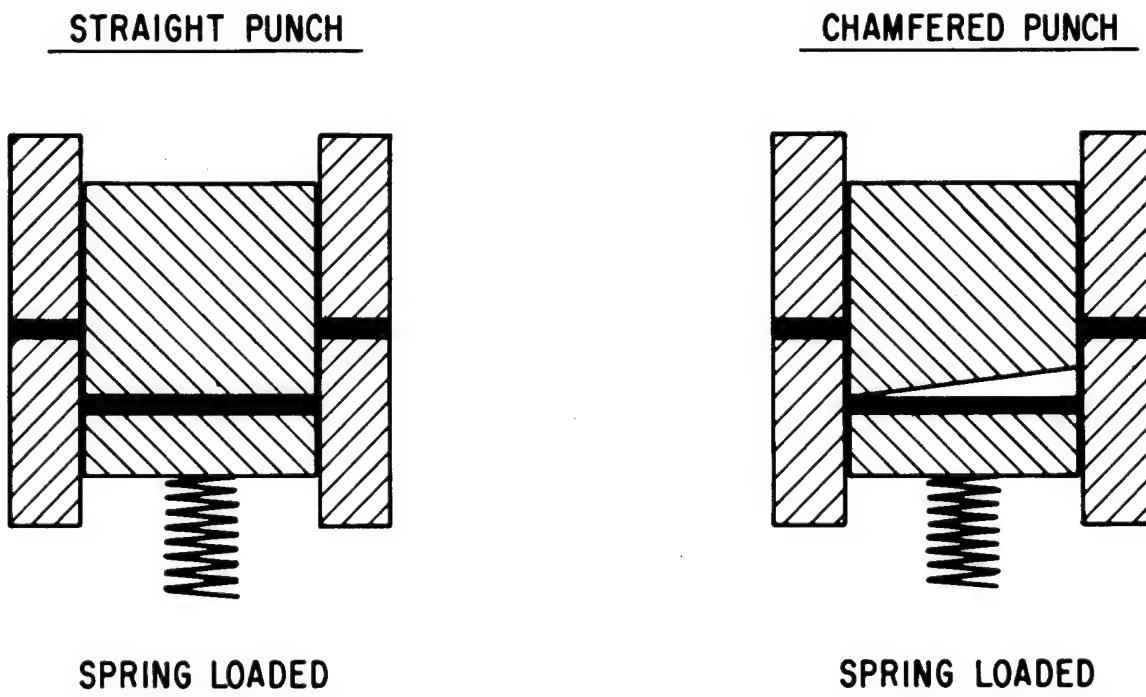
Figure 16

PLANETARY TRIMMER

MOTION OF
UPPER TRIMMING
DIE

TRIMMED
PART
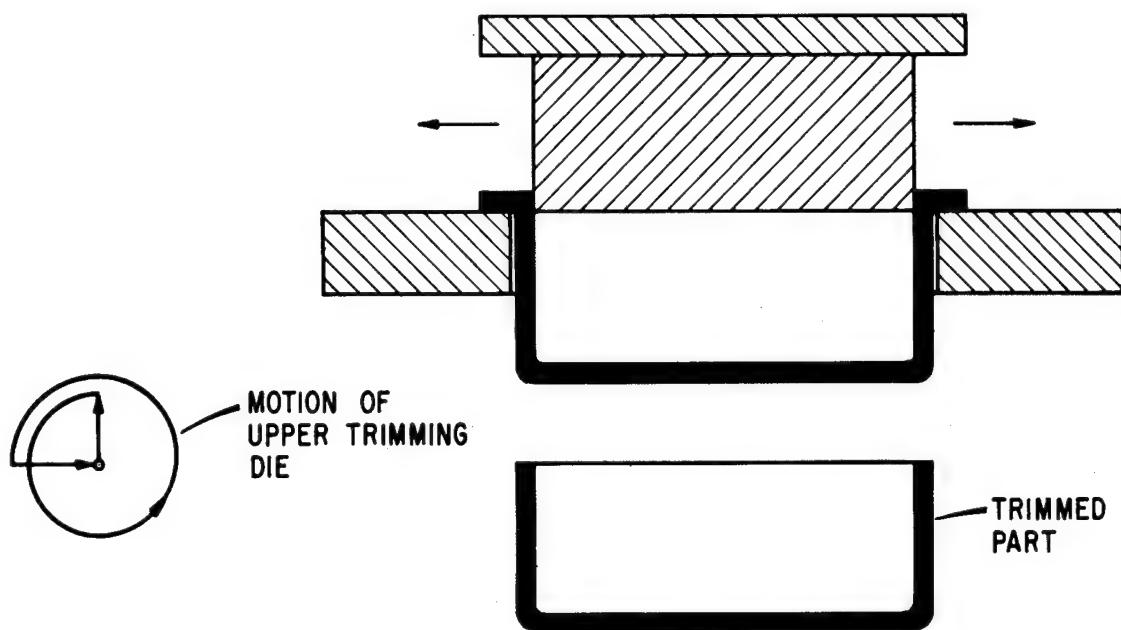
Figure 17

SINGLE-STAGE FORMING UNIT

1. HEAT

2. LOAD, FORM, & UNLOAD

PLUG TABLE

HEATER

CLAMP

FRAME

TRACK

HEATER

MOLD TABLE
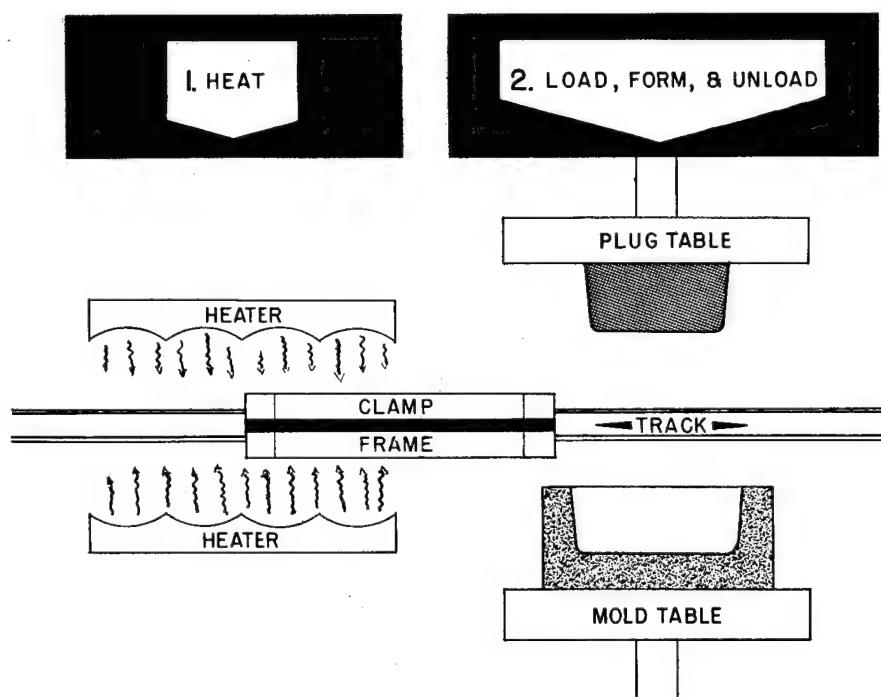
Figure 18

ROLL-FED SINGLE - STAGE UNIT

HEATER

ADVANCING MECHANISM

CLAMPING FRAME

MOLD TABLE
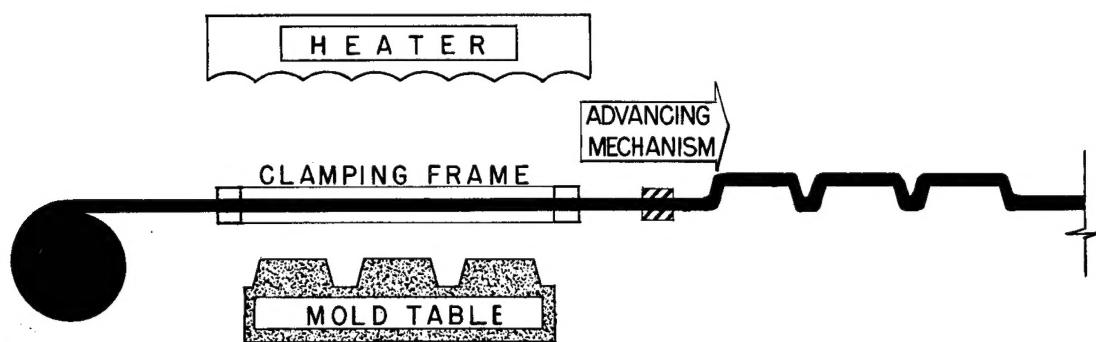
Figure 19

DOUBLE-STAGE FORMING UNIT

HEATER
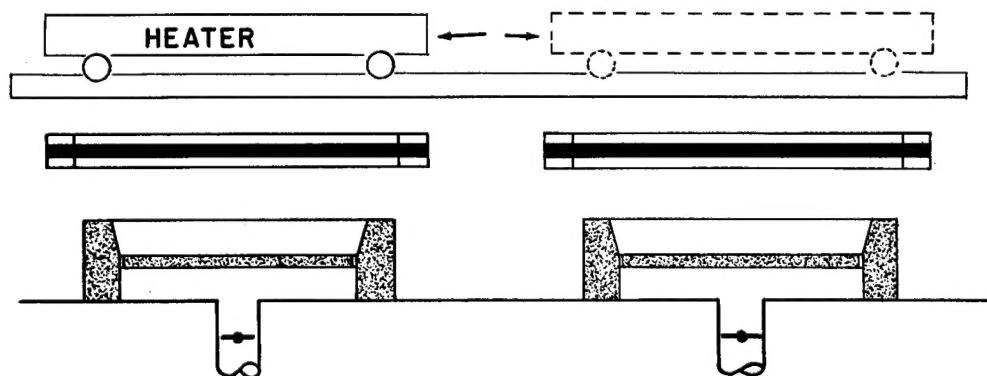
Figure 20

THREE - STAGE ROTARY UNIT
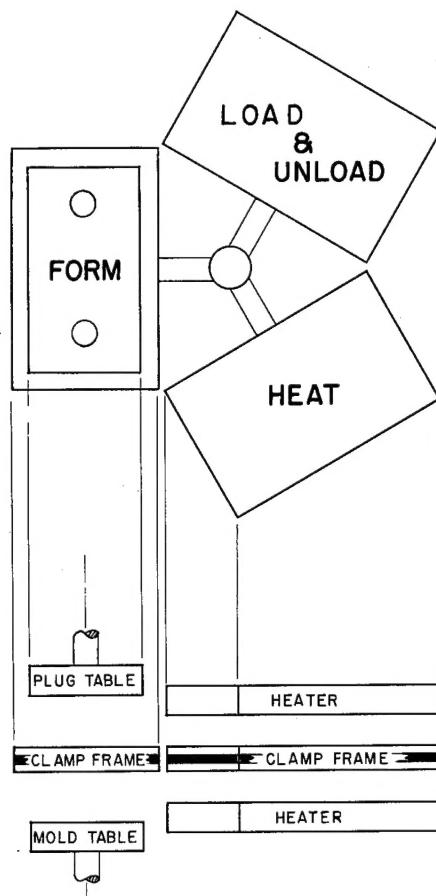
Figure 21

## *CONTINUOUS FORMING UNIT*
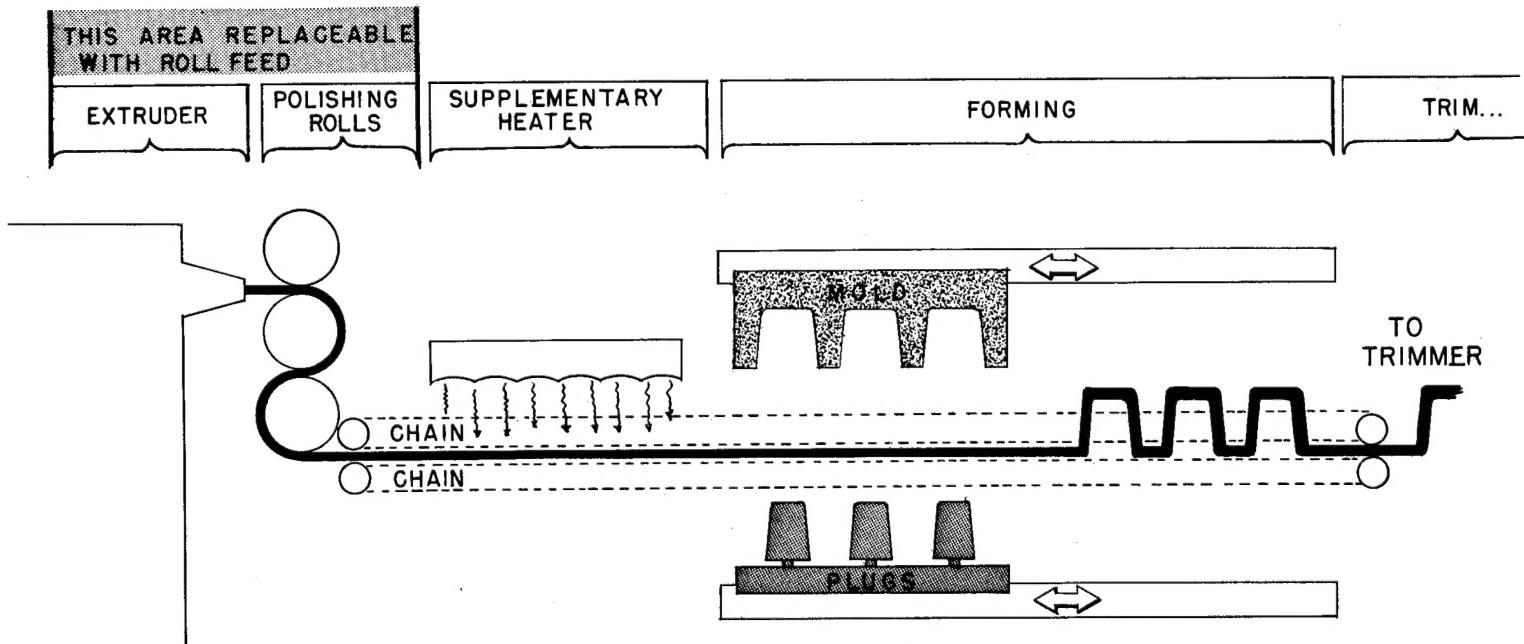
Figure 22

*DRUM FORMER*
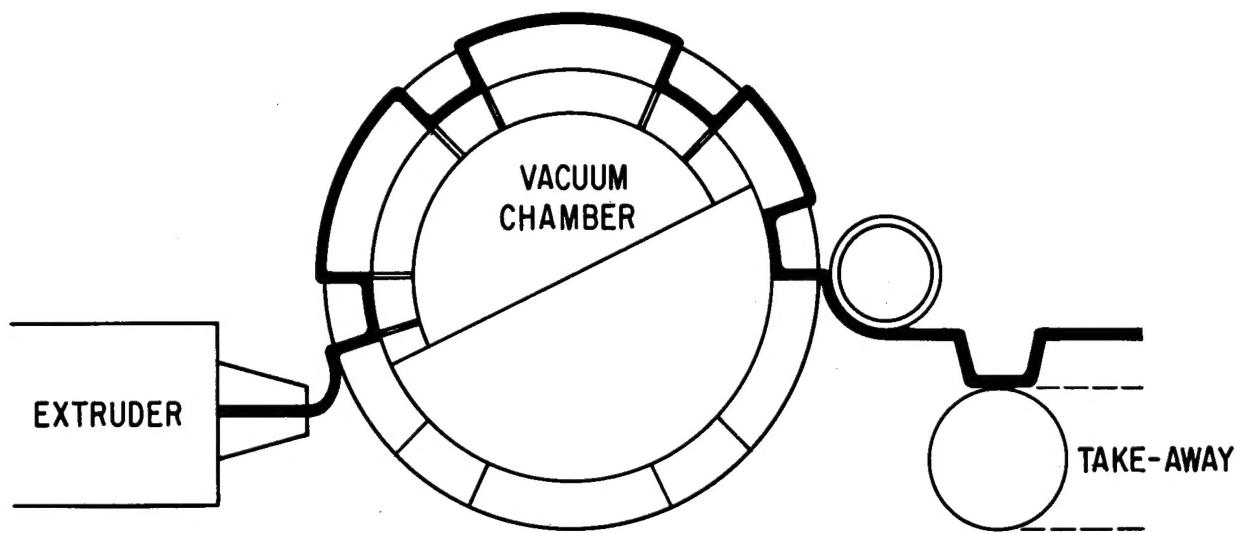
Figure 23

PART FORMED WITH ORPHAN INSERT
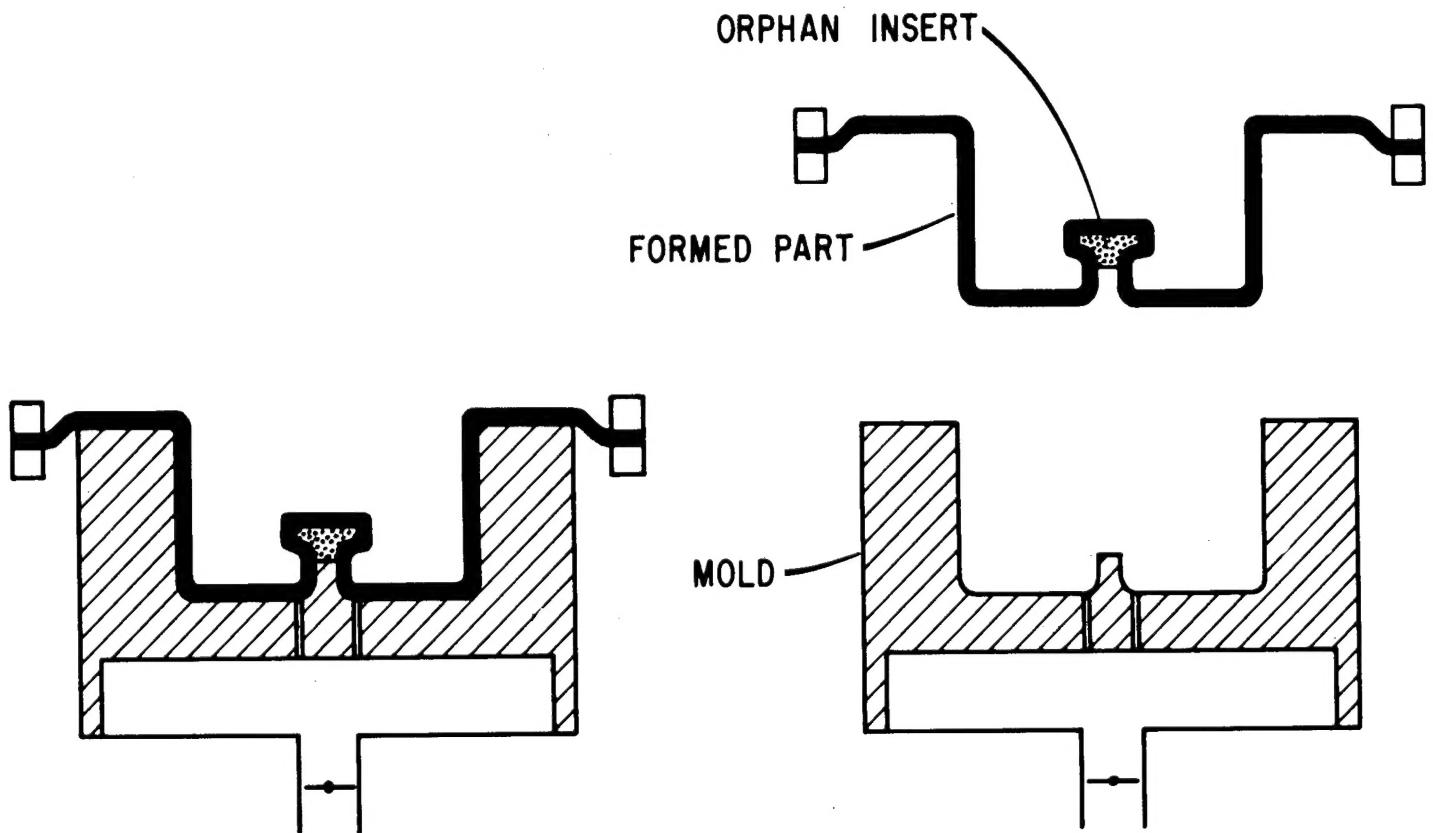
Figure 24

CAST ALUMINUM MOLD CORED FOR TEMPERATURE CONTROL

VENT HOLES TO
VACUUM CHAMBER

CORED PASSAGES FOR CIRCULATION
OF TEMPERATURE – CONTROL FLUID
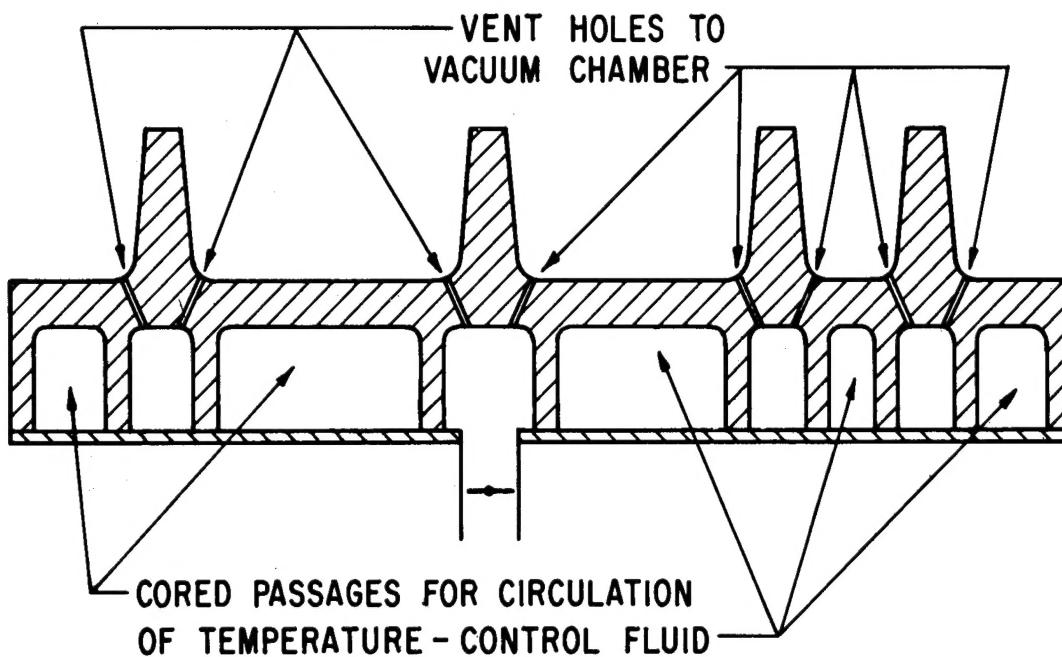
Figure 25

## A TYPICAL STACKING BOSS DESIGN
(H IS STACKING BOSS)

H > h

H

h

H

h
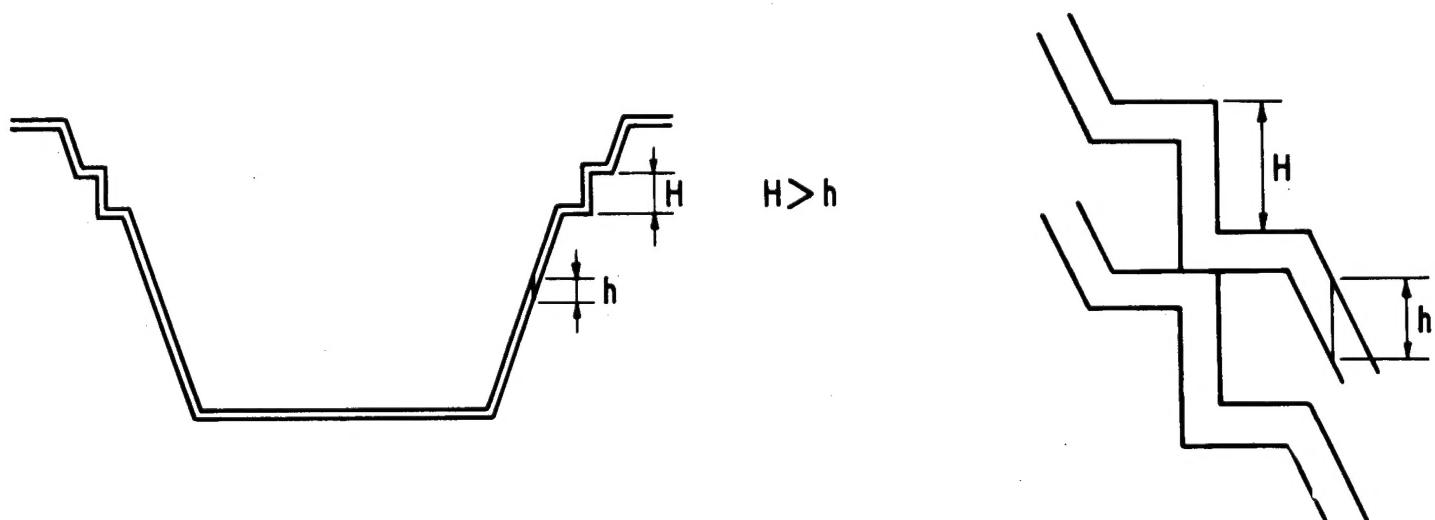
VIEW SHOWING TWO
PARTS STACKED